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Rayleigh backscattering minimization in single fiber colorless WDM-PON using intensity remodulation technique*

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The performance of colorless wavelength-division multiplexed passive optical network (WDM-PON) systems suffers from the transmission impairments mainly due to Rayleigh backscattering (RB). In this paper, we propose and demonstrate a single fiber colorless WDM-PON which enhances the tolerance to RB induced noise. The high extinction ratio in both return-to-zero (RZ)-shaped differential phase shift keying (DPSK) downstream (DS) data signal and intensity-remodulated upstream (US) data signal helps to improve the tolerance to RB induced noise. Simulation results show that downstream and upstream signals can achieve error-free performance at 10 Gbit/s with negligible penalty and improve the tolerance to RB induced noise over 25 km standard single-mode fiber.

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The wavelength-division multiplexed passive optical network (WDM-PON) has been considered as a promising next generation access network solution due to its ability to provide high bandwidth and flexibility. The network architecture, which is with centralized light source at the optical line terminal (OLT) and data remodulation part using downstream (DS) signal received at the optical line unit (ONU), is an attractive solution for low-cost implementation of the upstream (US) transmitter[1]. Using a single feeder fiber for both downstream and upstream transmissions in a full duplex arrangement can further reduce the deployment cost of the WDM-PON[2]. However, the performance of a single fiber colorless WDM-PON system undergoes the transmission impairments due to Rayleigh backscattering (RB) induced noise. In optical colorless transmission, there are two types of RB effects which can degrade upstream transmission. One is the back reflection of the continuous wave (CW) light, and the other is the back reflection of the upstream modulated signal. It causes the degradation in upstream signal and deteriorates the bit-error-rate (BER) of receiver at OLT[3].

In recent years, various remodulation schemes have been proposed to achieve robust performance of both downstream and upstream transmissions. Novel devices, such as reflective silicon optical amplifier (RSOA), have been proposed to decrease RB induced cross-talk in WDM-PONs using pulse broadening, multi-wavelength source and cross-seeding schemes[4-6]. To enhance tolerance to RB induced noise in WDM-PONs, different modulation formats, such as optical suppressed sub-carrier modulation and phase modulation, have also been proposed[7,8]. In addition, the techniques based on noise predictive equalization, line coding and ring based WDM-PON were reported to reduce the effect of RB induced noise in WDM-PONs[9-11]. However, these schemes either use complex modulation formats with high deployment cost or need extra circuits and devices at ONU. Jing Xu[12] proposed a scheme based on phase remodulation WDM-PON instead of the approach based on carrier distribution. It has been shown that reducing modulation depth of downstream differential phase shift keying (DPSK) signal can make the upstream signal more robust to RB induced noise.

In this paper, we propose and demonstrate an intensity remodulation scheme which improves RB tolerance in a colorless 10 Gbit/s WDM-PON with a single feeder fiber. The downstream DPSK signal is generated by a $LiNbO_3$ Mach-

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Zehnder modulator driven by return-to-zero (RZ)-shaped differentially pre-coded data. Reducing the modulation depth of the downstream DPSK signal can enhance the tolerance of the upstream signal against the RB induced noise. Compared with prior schemes, the downstream DPSK signal is generated without pulse carving to alleviate the complexity and cost of transmitter.

There are two basic components of RB which interferes with the upstream data signal when it propagates from ONU to OLT in a conventional single feeder WDM-PON as shown in Fig.1.

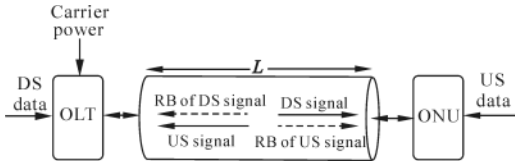


Fig.1 Path of two back reflection signals in a conventional single feeder WDM-PON

The first component is the carrier backscattering of P_{CB}, which is generated by the carrier delivered to ONU, and can be expressed as[13,14]

$$P_{CB} = P_C B[1 - \exp(-2\alpha L)] , \quad (1)$$

where P_C is the carrier power injected into the fiber, L is the fiber length, and $B=S\alpha_s/2\alpha$ with the fiber scattering coefficient of α_s (km^{-1}), the fiber recapture coefficient of S (dimensionless) and the attenuation coefficient of α (km^{-1}).

The second component is the signal backscattering of P_{SB} which is generated by the modulated upstream data signal. The back scattered signal re-enters the ONU where it is re-modulated and reflected towards the receiver at OLT. P_{CB} can be expressed as

$$P_{SB} = P_C B(1-l^2)l^2 g^2 \ . \quad (2)$$

This noise can create RB again resulting in continuous iterative process. Thus Eq.(2) develops into

$$P_{SB} = P_C l^2 \sum_{n=1}^{\infty} B^n (1-l^2)^n g^{n+1} \ . \quad (3)$$

The spectrum of P_{CB} remains the same as that of CW carrier, whereas the spectrum of P_{SB} becomes broad, as it is modulated twice at ONU. It is noted that under normal conditions, this expression depends on the squared gain which may lead to the limitations of systems .

The proposed WDM-PON is shown in Fig.2. An OLT consists of distributed feedback laser diode (DFB-LD) arrays which offer the wavelengths from λ_1 to λ_4 for downstream data. By choosing an appropriate biased voltage for Mach-Zehnder modulator (LiNbO$_3$-MZM) and applying a super imposed electrical signal for clock and data, the LiNbO$_3$-MZM generates an optical signal which is RZ-shaped and modulated using a single modulator. The generated downstream DPSK signals are multiplexed and transmitted over a 25 km standard single-mode fiber (SSMF) using a single feeder fiber configuration. On the other end, an demultiplexer is used to demultiplex the downstream signal and send them to ONU. At ONU, a portion of the downstream received optical power is tapped off by a half power splitter (PS). The downstream DPSK signal with constant intensity is demodulated by a 1 bit delayed interferometer (DI) and balanced photo diodes. The rest of the downstream optical signal is remodulated by an intensity modulator (IM) of 10 Gbit/s RZ-OOK. The generated upstream signal is transmitted back to the OLT using SSMF through a complete path. However, regarding the typical OLT configurations, the up- and down-link paths are merged by an optical circulator (C), and therefore a possible reflection is strongly attenuated. Fig.3 shows the waveforms of four downstream DPSK and upstream OOK multiplexed signals via optical spectrum analyzer.

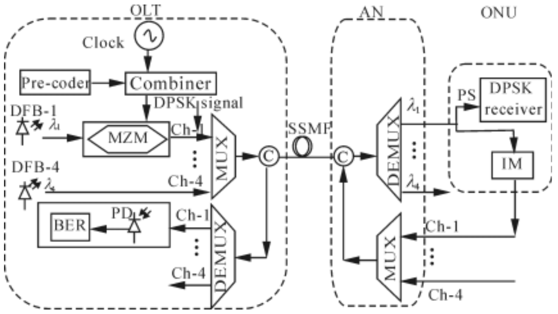
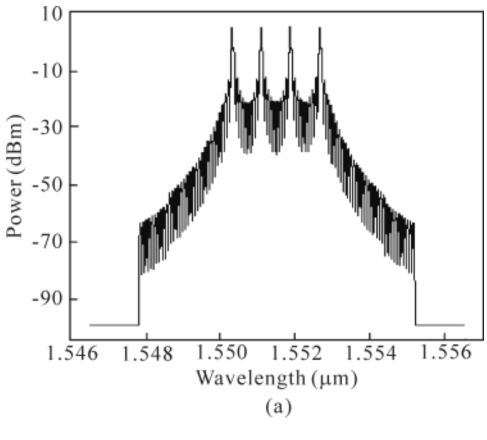


Fig.2 Schematic diagram of the single feeder full duplex WDM-PON system

To discuss the performance of the proposed WDM-PON system, we establish a model for simulation using Optisystem v.8.0 according to the network architecture as shown in Fig.2. A 10 Gbit/s pseudorandom bit stream (PRBS) data with or-



(a)

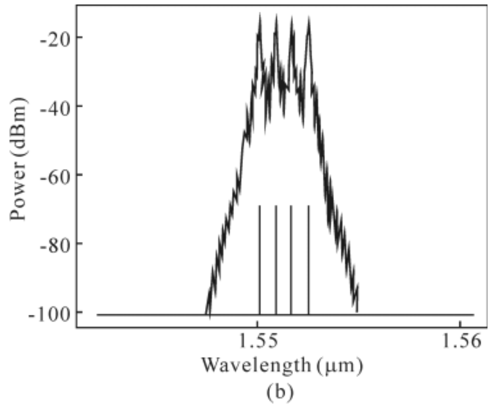


Fig.3 (a) Four downlink multiplexed DPSK signals and (b) four uplink multiplexed OOK signals

der of 2^7-1 is superimposed on a 5 GHz clock using a combiner. The superimposed signal is externally modulated by a $LiNbO_3$-MZM to generate RZ shaped-DPSK downstream data signal. Four continuous light waves with launch power of 10 dBm are generated using distributed feedback (DFB) lasers at wavelengths of 1552.52 nm, 1552.12 nm, 1551.72 nm and 1551.32 nm for four different channels, respectively. They are multiplexed and transmitted over 25 km SSMF. At the access node, a 3 dB optical splitter divides the downstream signal into two parts. An intensity modulation technique of 10 Gbit/s OOK is used to remodulate the first part from the power splitter to generate upstream data signal. The second part from the power splitter is demodulated by a 1 bit delayed interferometer (DI) and balanced photo diodes. However, regarding typical OLT configurations, the uplink and downlink paths are merged by means of optical circulators. The general settings of the fiber used in our simulation are given in Tab.1.

Tab.1 Simulation parameters

Parameter	Value
Dispersion parameter of SSMF	17 ps/(nm • km)
Dispersion slope of SSMF	0.075 ps/(nm^2 • km)
Attenuation coefficient of SSMF	0.2 dB/km
Effective core area of SSMF	80 μm^2
Nonlinear index-coefficient of SSMF	2.6×10^{-20}
Responsitivity of photodetector	1 A/W
Dark current of photodetector	10 nA
Rayleigh backscattering	5×10^{5} km^{-1}

The BERs as a function of received optical power for both the downstream and upstream transmissions for channel-1(Ch-1) and channel-3(Ch-3) are shown in Fig.4 using back to back (B2B) condition. In the downstream, the 10 Gbit/s DPSK data signal provides a BER of 10^{-9} at received power of -34 dBm, while in the upstream, the 10 Gbit/s OOK data signal provides a BER of 10^{-9} at received power of -24 dBm.

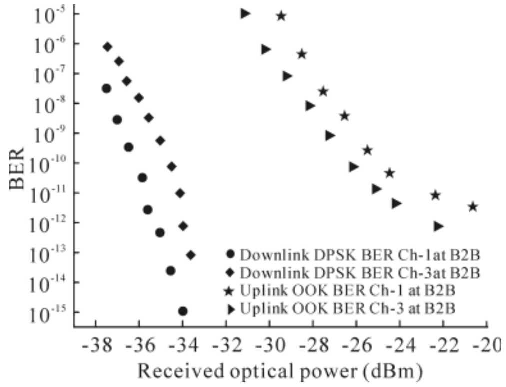


Fig.4 BERs of downlink and uplink transmissions at B2B for Ch-1 and Ch-3

The BERs as a function of received optical power for downstream and upstream data signals after propagating in 25 km SSMF are shown in Fig.5. In the downstream, the 10 Gbit/s DPSK data signal provides a BER of 10^{-9} at received power of -32 dBm, while in the upstream, the 10 Gbit/s OOK data signal provides a BER of 10^{-9} at received power of -21.5 dBm. In upstream, a power penalty of 2.5 dB relative to B2B case has been observed at BER of 10^{-9} after propagating in 25 km SSMF. Such a power penalty could be largely attributed to two basic components of RB, i.e., the carrier backscattering and the signal backscattering along with chromatic dispersion. However, the constant performance of both downstream and upstream signals clearly illustrates the applicability of such a low-cost scheme for the implementation in future WDM-PONs.

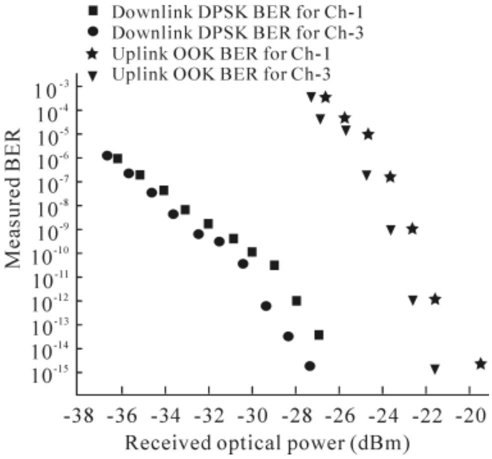


Fig.5 BERs for downlink and uplink signals after propagating in 25 km SSMF for Ch-1 and Ch-3

The average power penalty of all the four multiplexed DPSK downstream signals at a BER of 10^{-9} is about 2.0 dB after 25 km transmission in single feeder fiber architecture without any signal amplification or dispersion compensation. On the other hand, the average power penalty for using four multiplexed intensity-modulated OOK upstream signals at a BER of 10^{-9} is 2.5 dB after the corresponding transmission over a complete path without any signal amplification or dispersion compensation.

Therefore, it is evident from the above results that an error-free transmission is achieved for both downstream and upstream directions without using any optical amplifier or dispersion compensation modules[11] to alleviate complexity and cost of the system. Fig.6 shows the corresponding optical eye diagrams for downlink and uplink channels. The eyes are clear and widely open.

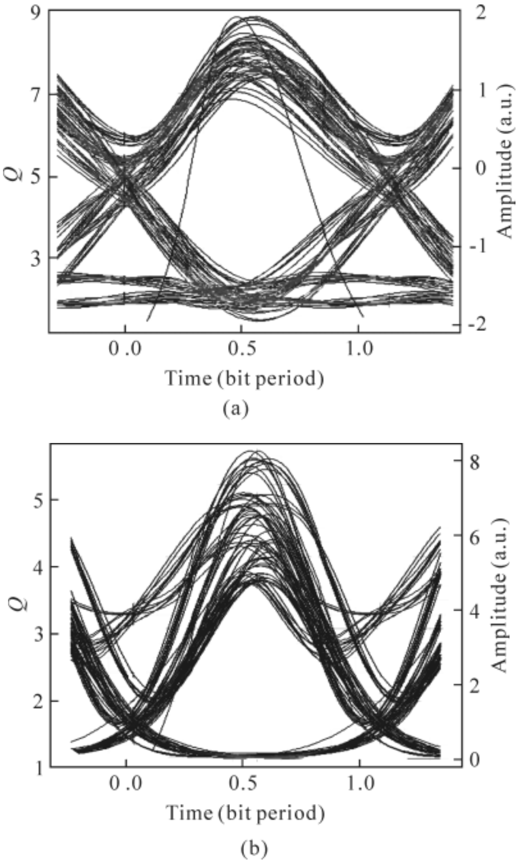


Fig.6 Eye diagrams for (a) DPSK downlink and (b) OOK uplink channels

We propose and demonstrate a single-fiber colorless WDM-PON architecture with improved tolerance to impairments induced by Rayleigh backscattering. It is demonstrated that the high extinction ratio in both RZ-shaped DPSK downstream and intensity-remodulated upstream data signals can help to increase the tolerance against the RB. The power penalties of symmetric 10 Gbit/s downstream and upstream data signals at BER of 10^{-9} are 2.0 dB and 2.5 dB, respectively. An error-free colorless transmission is achieved over a distance of 25 km without using any optical amplifier or dispersion compensation modules to alleviate the complexity and cost of the system.

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